Basis for Depth Aggregation of GEMSS Model Output for Budd Inlet TMDL

Three dimensional models represent the water column using vertical discretization schemes to make computations feasible. The basis for horizontal model grid size and vertical layering used for this work was described in Roberts et.al. (2014). This section focuses on the basis for depth aggregation of model output. The objective of depth aggregating vertical layers is to represent model output at temporal and spatial scales needed for policy determinations, without averaging out, or diluting features that are relevant to the water quality standard and criteria. Water quality standards and criteria are not specified to correspond with any specific depth, but rather to apply to the water body in its entirety. Thus, biochemical, physical and policy considerations come into play when aggregating model output for dissolved oxygen (DO), as described below. Depth aggregation for DO model output is based on:

Commented [ZC1]: Does it make sense to describe the basis for model grid size first and then describe rationale for aggregating output?

Commented [WL(2R1]: I think we did this in a previous report (not sure if this the correct one, but have put in while I confirm).

- Habitat Considerations to meet Marine Water Designated Uses (refer to Appendix 1)
- Tidal range, vertical stratification and biological productivity in euphotic zone layer

1. <u>Habitat considerations</u>

Budd Inlet south of Priest Point Park is designated Good Quality Aquatic Life, while the rest of Budd Inlet is Excellent Quality Aquatic Life. The marine DO standard has two parts. First, the standards establish minimum criteria that vary with designated use: (1) To protect the Excellent Quality category of aquatic life use, the lowest 1-day minimum oxygen level must not fall below 6.0 mg/L more than once every 10 years on average. (2) To protect the Good Quality category of aquatic life use, the lowest 1-day minimum oxygen level must not fall below 5.0 mg/L more than once every 10 years on average. Excellent and good quality designations are further defined in the regulation, WAC 173-201A-210:

(ii) **Excellent quality** salmonid and other fish migration, rearing, and spawning; clam, oyster, and mussel rearing and spawning; crustaceans and other shellfish (crabs, shrimp, crayfish, scallops, etc.) rearing and spawning.

(iii) **Good quality** salmonid migration and rearing; other fish migration, rearing, and spawning; clam, oyster, and mussel rearing and spawning; crustaceans and other shellfish (crabs, shrimp, crayfish, scallops, etc.) rearing and spawning.

Numeric criteria are meant to apply to ecosystem habitats. The assumption is that if the numeric criteria are met for sensitive organisms of each habitat, then the ambient condition of the waterbody as a whole will protect all other species. It is recognized that in some situations where the numeric criteria are insufficient to protect all fish and non-fish species, the narrative criteria may need to be applied to set alternative criteria, but the numeric criteria is set to protect the species listed nonetheless. (Brown, 2016)

Commented [ZC3]: Is there a reg or policy document available that could be referenced here?

Commented [WL(4R3]: We are looking into this.

Depths in Budd Inlet range from 100 ft (30 m) in the north to mudflats in the shallow East and West Bays. Much of the inlet varies from 15 to 50 ft (5 to 15 m) in depth. The species listed above, and their prey, can inhabit the entire Budd Inlet water column. For instance, the native Olympia Oyster (*Ostrea Lurida*) are found at depths from 0-71m (Couch, et. al. 1989). Furthermore, organisms that inhabit the bottom, termed benthic organisms, are an important part of the food chain from which fish and non-fish species depend on. Vaquer-Sunyer, et.al point out that benthic organisms are especially vulnerable to hypoxia because sediments tend to be depleted

Commented [WL(5]: Updated source and put in references as requested by Chris.

first relative to the overlaying water column. Thus, when determining whether standards are met throughout the water column, it is important to consider the bottom depths.

2. Tidal range, vertical stratification and euphotic zone considerations

The euphotic zone is defined as the area in the water column that receives sufficient light for photosynthesis to occur. We agree with Banas et.al (2015) use of 30 m as reflective of the euphotic layer in Puget Sound. In the euphotic zone oxygen is produced, and thus averaging euphotic layers along with the rest of the water column will result in masking of potential hypoxic layers at depth. Since Budd Inlet is within the 30 m euphotic zone, we exclude from the aggregation computation only the top layers that are generally separated from the rest of the water column due to stratification. However, in shallow nearshore areas, salinity-depth profiles indicate that the water column is well mixed, and so, we include the entire sub-tidal water column in those areas[1].

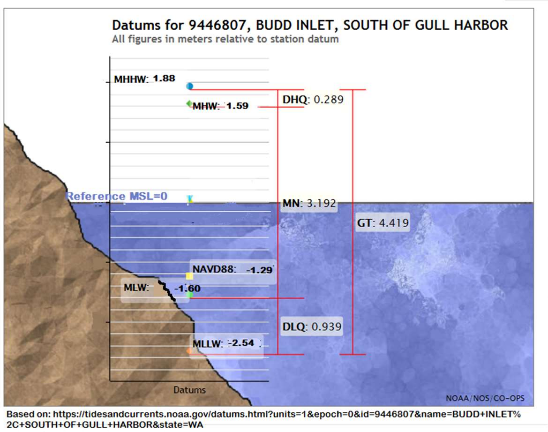


Figure 1. Budd Inlet Tidal Range

The tidal range in Budd Inlet is around 4.2 m (Figure 1), based on the difference between mean higher high water and mean lower low water; however, tidal range for spring tides can exceed 5.5 m as measured in 1996-1997 at Boston harbor during the Budd Inlet Scientific Study (Aura Nova Consultants, 1998). A plot of the observed data is included in Figure 2. We exclude areas above the subtidal range, defined in this case as areas above the minimum low water line, because these areas are very shallow, subject to going dry, and when they are wet, are generally expected to be oxygenated due to wind and wave action.

Commented [ZC6]: You may want to consider including a discussion of the proposed temporal aggregation scheme as well – and how such scheme protects use etc.

Commented [WL(7R6]: See foot note added in – was not sure where else to put this.

Commented [WL(8]: Replaced discard with exclude.

Commented [ZC9]: In most cases, this is likely true. Are there shallow water locations near LOTT that may have a substantive deficit? It might be worth describing the range of deficits predicted in shallow areas to justify exclusion.

Commented [WL(10R9]: We have added a reference to Figure 7. This shows that the shallow layers have a higher DO than those below (which are aggregated together).

[1] We do not include a discussion of temporal aggregation in this paper. However, we used lowest value per day (the one day minimum) was used to determine if a violation of standards occurred. This adheres to the water quality standard, see WAC (173 201A – 1D)

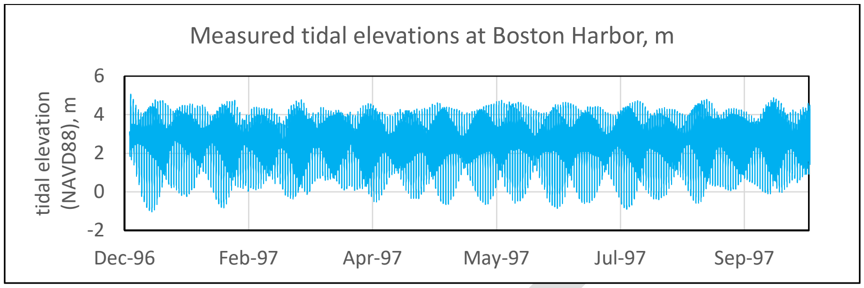


Figure 2. Tidal elevations measured at Boston harbor (1997)

The GEMSS model used for Budd Inlet uses a Cartesian (z-coordinate system) for vertical discretization. The first top ten layers are of equal thickness (1 m). Layers 11 and 12 are 2 m thick, and the layers after that 3 m, as shown in Figure 3. We start aggregating at sub-tidal depths (below 6 m—or layer 7). Layers above this depth are never included in the averages since they are not consistently submerged in water, as described above.

Appendix 2 shows salinity-depth profiles for Budd Inlet at different stations and seasons in 1997, the year that the modeling scenarios take place. Salinity-depth profiles are used here as an indication of the degree of mixing in the water column. We acknowledge that vertical profiles are subject to temporal variation. Nonetheless, observed salinity profiles available remain generally uniform throughout the depth of various shallow stations (generally between 0- 12 m), indicating a well-mixed subtidal zone. The scheme utilized for vertical aggregation accounts for that fact: at subtidal depths between 6-12 m, we aggregate and average all layers, assuming complete mixing.

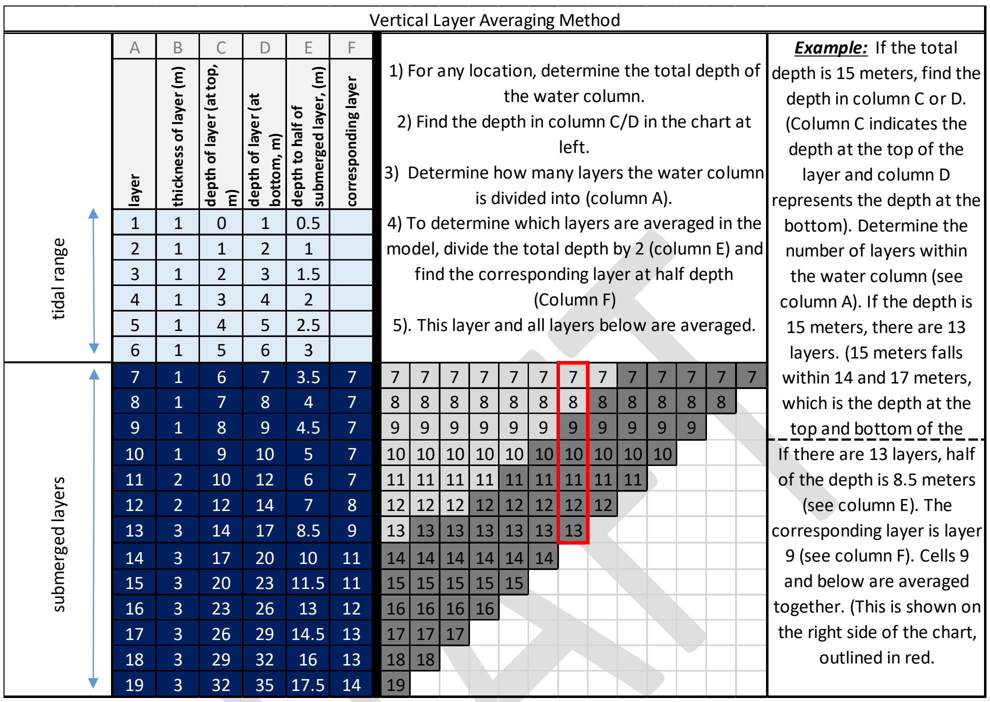
Very little observational data is available for deeper stations (12 m and below) for 1997. However, more recent profiles obtained in 2015 indicate that some degree of stratification may occur at mid-levels—starting around 6 m (Figure 4-6). Therefore, to remain protective of all habitats in Budd Inlet, and exclude higher euphotic levels rich in oxygen localized on top, we recognize that stratification can occur at mid-levels, half-way in the water column when the total depth of the water column is 12 m or greater. Thus, for all depths greater than 12 m, we average the layers comprised between half of their depth, down to the bottom, as shown in the dark grey boxes in Figure 3.

Commented [ZC11]: Consider describing rationale for using the arithmetic mean for representing DO in multiple layers. What about the minimum or lower quartile DO? Why is the arithmetic average protective of the use?

Commented [WL(12R11]: There are many different ways we could have chosen to do this. Since we already removed the top most layers (thereby getting rid of all of the higher values) we feel using an average is appropriate.

Commented [ZC13]: We would encourage a little more discussion to explain Figure 3. It is a great and succinct graph, but understanding it required your and Andrew's patient explanation.

Commented [WL(14R13]: See updated Figure with additional explanation.



A	B	C	D	E	F
layer	thickness of layer (m)	depth of layer (at top, m)	depth of layer (at bottom, m)	depth to half of submerged layer, (m)	corresponding layer
1	1	0	1	0.5	
2	1	1	2	1	
3	1	2	3	1.5	
4	1	3	4	2	
5	1	4	5	2.5	
6	1	5	6	3	
7	1	6	7	3.5	7
8	1	7	8	4	7
9	1	8	9	4.5	7
10	1	9	10	5	7
11	2	10	12	6	7
12	2	12	14	7	8
13	3	14	17	8.5	9
14	3	17	20	10	11
15	3	20	23	11.5	11
16	3	23	26	13	12
17	3	26	29	14.5	13
18	3	29	32	16	13
19	3	32	35	17.5	14

Figure 3. Vertical aggregation scheme for Budd Inlet.

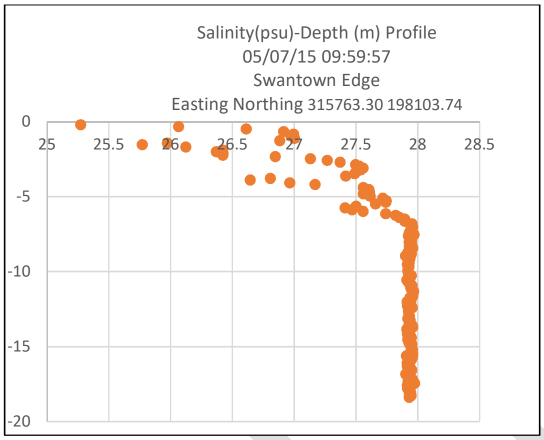


Figure 4. Salinity depth profile near Swantown Marina, Budd Inlet (Courtesy of: Coastal Monitoring and Analysis Program, SEA, Department of Ecology).

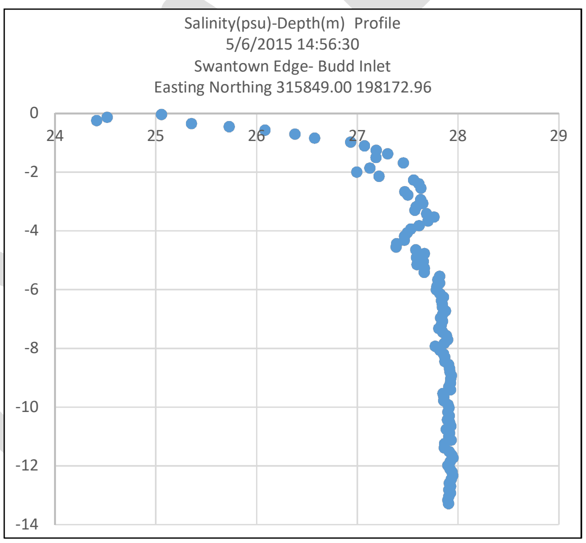


Figure 5. Salinity depth profile near Swantown Marina, Budd Inlet (Courtesy of: Coastal Monitoring and Analysis Program, SEA, Department of Ecology).

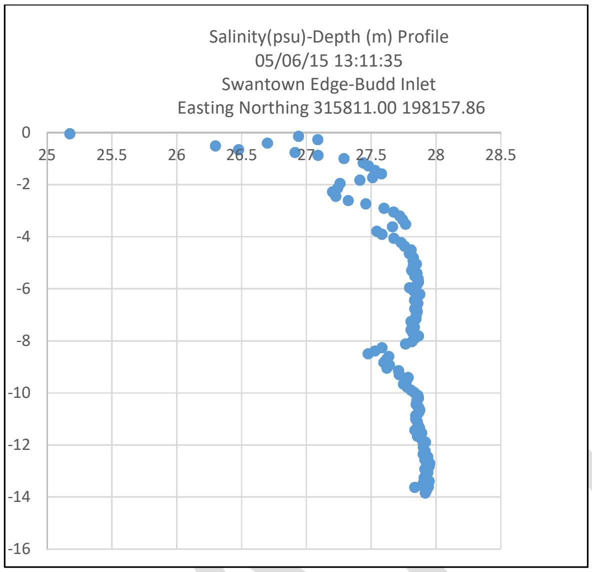


Figure 6. Salinity depth profile near Swantown marina, Budd Inlet (Courtesy of: Coastal Monitoring and Analysis Program, SEA, Department of Ecology).

Figure 7 shows the DO concentrations at four locations within Budd Inlet (in black) that are used in the vertical aggregation scheme described above—DO concentrations at the surface (in blue) are not incorporated into the aggregation scheme so that the resulting aggregated values are protective of biological organisms , and thus water quality criteria are met, throughout the entirely of the water column.

Commented [ZC15]: Does this mean criteria are achieved throughout the water column?

Commented [FC(16]: Added language to address this comment.

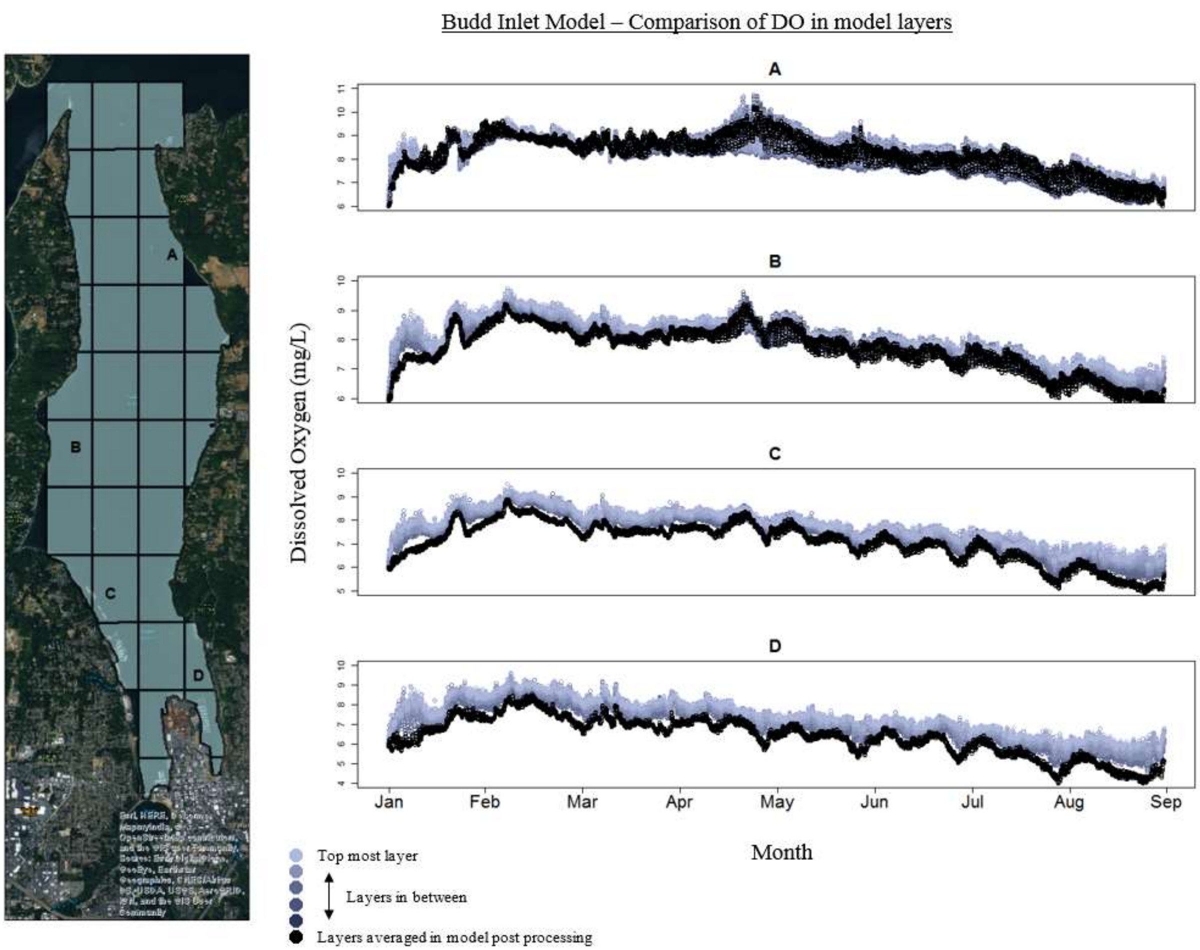


Figure 7. Comparison of DO in model layers

Commented [ZC17]: Great graphic! May want to include Oct, Nov, Dec in these plots.

Commented [FC(18]: Did not model those months.

Basis for Horizontal Aggregation of GEMSS Model Output for Budd Inlet TMDL

Ecology uses county quadrangle grids (Figure 8) to designate locations in which exceedances of the dissolved oxygen standard in marine waters have been measured. This is the same grid system used in Water Quality Assessment (also known as 303(d) list). This grid was chosen for its convenience and has the additional benefit of being relevant to the 303(d) listings. Since DO in Budd Inlet is fairly horizontally homogenous using the established 303(d) grid does not mask areas with low dissolved oxygen, and is protective of the habitat. It is important to note that this approach may not be applicable throughout the Salish Sea.

Commented [ZC19]: Would encourage a bit more quantitative statement here – perhaps a figure like Fig. 7 only applied to horizontal.

Commented [FC(20]: See plot below.

The methodology for horizontal averaging involves overlaying the 303(d) grid over the model's grid, and averaging the model grid cells that fall within each 303(d) grid layer as depicted in Figure 8. The resulting averages (including vertical and horizontal aggregation) are shown in Figure 9.

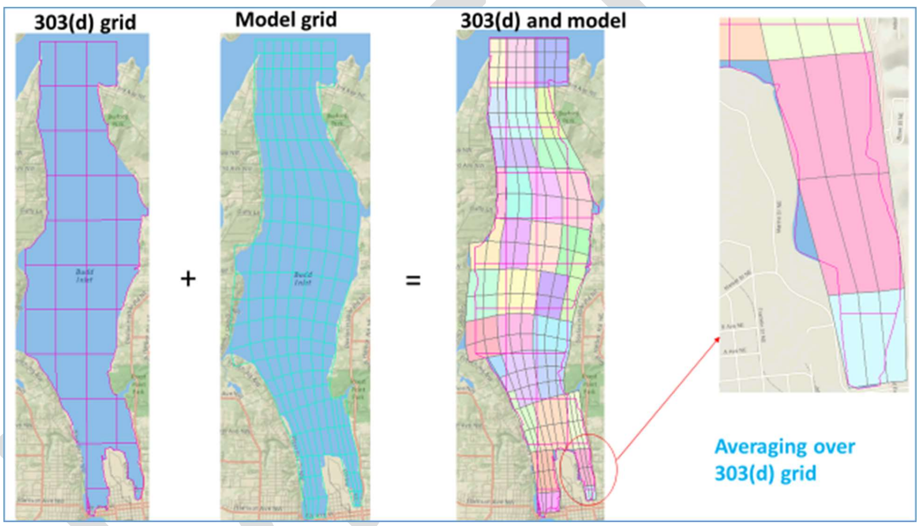


Figure 8. Plan view of the Budd Inlet 303(d) grid layers, GEMSS Grid and their resulting overlay

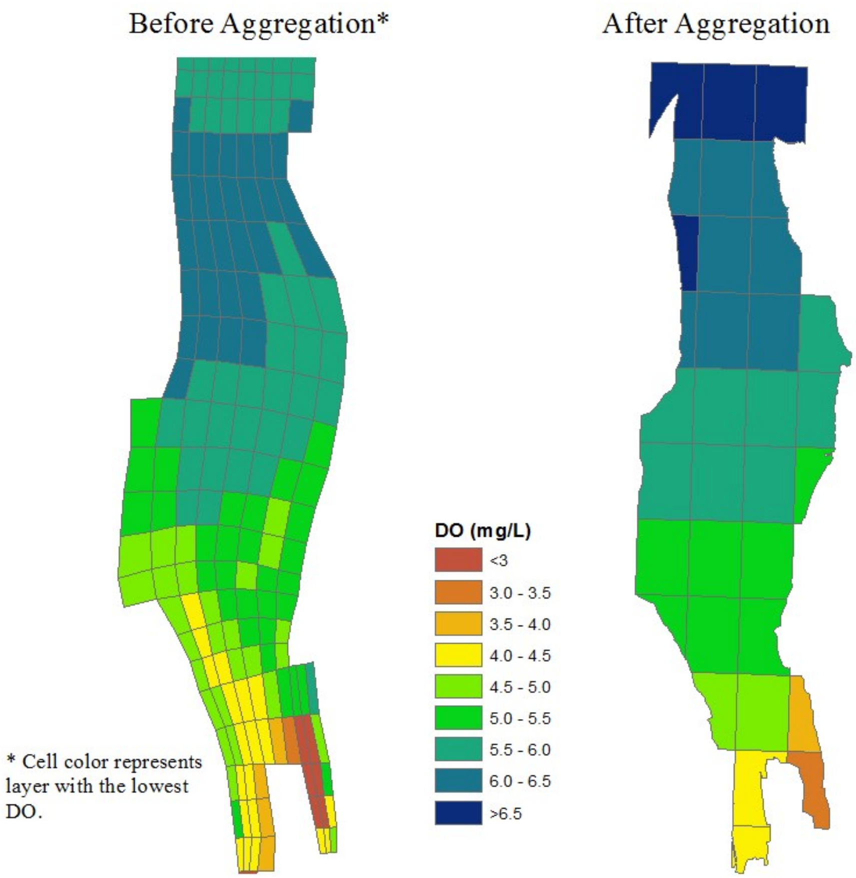


Figure 9. Comparison of DO concentrations for GEMSS grid (showing lowest value) and 303(d) grids (showing average value after aggregation methods applied).

References

Aura Nova Consultants, Inc. and J.E. Edinger Associates, Inc. 1998. Budd Inlet Scientific Study Final Report. August, 1998

Banas, N.S., Conway-Cranos, L., Sutherland, D.A. Patterns of River Influence and Connectivity Among Subbasins of Puget Sound, with Application to Bacterial and Nutrient Loading. *Estuaries and Coasts* (2015) 38: 735

Brown, Chad, WA Department of Ecology e-mail, Discussion of the marine D.O. criteria compliance point. Thu 11/3/2016 9:36 AM

Couch, D., and Hassler, T., (1989) Species Profiles: Life histories and Environmental Requirements of Coastal Fishes and Invertebrates (Pacific Northwest) Olympia Oyster, Biological Report 82(11.124), U.S. Fish and Wildlife Service

Roberts, M. ,Albertson, A., Ahmed, A., Pelletier, G., South and Central Puget Sound Water Circulation and Development, 2014. Washington Department of Ecology, Publication 14-03-015

Vaquer-Sunyer, R., Duarte, C. Thresholds of Hypoxia for Marine Biodiversity, *PNAS* (2008) 105:40.

Appendix 1.

173-201A-210

Marine water designated uses and criteria.

The following uses are designated for protection in marine surface waters of the state of Washington. Use designations for specific water bodies are listed in WAC 173-201A-612.

(1) **Aquatic life uses.** Aquatic life uses are designated using the following general categories. It is required that all indigenous fish and nonfish aquatic species be protected in waters of the state.

(a) **The categories for aquatic life uses are:**

(i) **Extraordinary quality** salmonid and other fish migration, rearing, and spawning; clam, oyster, and mussel rearing and spawning; crustaceans and other shellfish (crabs, shrimp, crayfish, scallops, etc.) rearing and spawning.

(ii) **Excellent quality** salmonid and other fish migration, rearing, and spawning; clam, oyster, and mussel rearing and spawning; crustaceans and other shellfish (crabs, shrimp, crayfish, scallops, etc.) rearing and spawning.

(iii) **Good quality** salmonid migration and rearing; other fish migration, rearing, and spawning; clam, oyster, and mussel rearing and spawning; crustaceans and other shellfish (crabs, shrimp, crayfish, scallops, etc.) rearing and spawning.

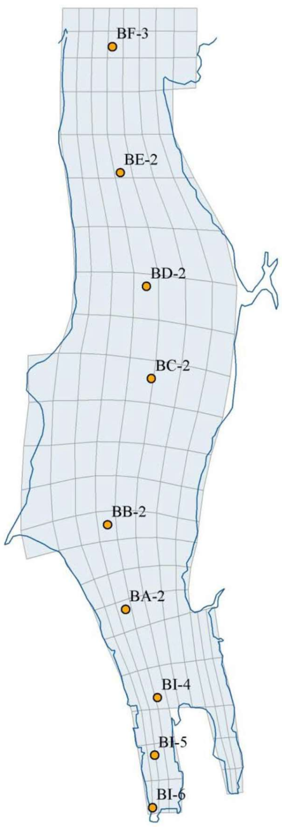
(iv) **Fair quality** salmonid and other fish migration.

(b) **General criteria.** General criteria that apply to aquatic life marine water uses are described in WAC 173-201A-260 (2)(a) and (b), and are for:

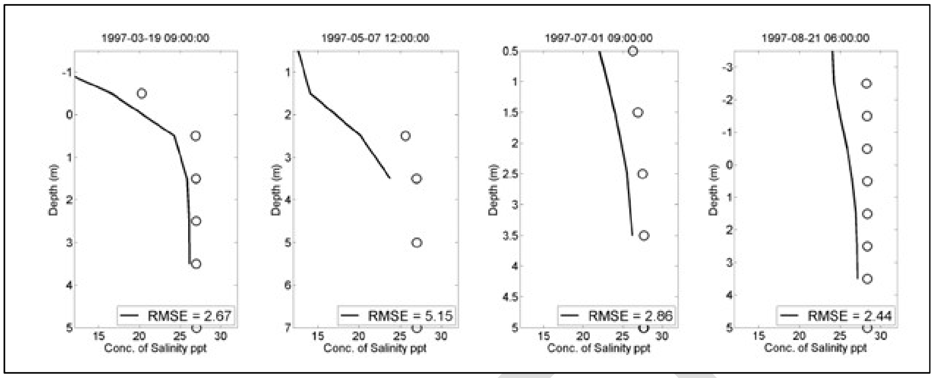
(i) Toxic, radioactive, and deleterious materials; and

(ii) Aesthetic values.

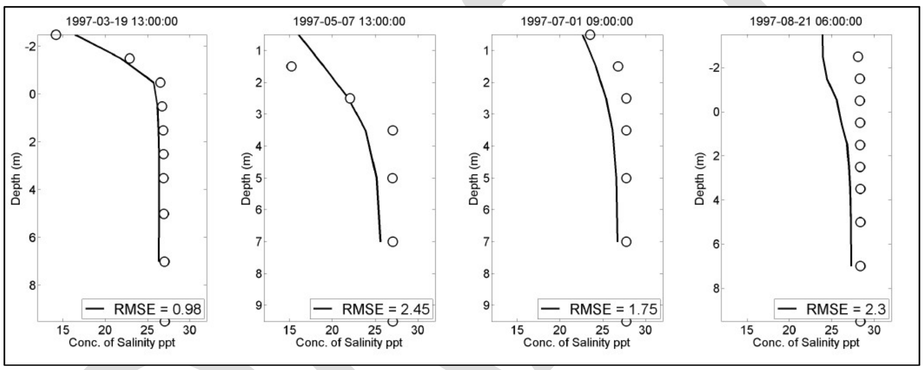
Appendix 2.



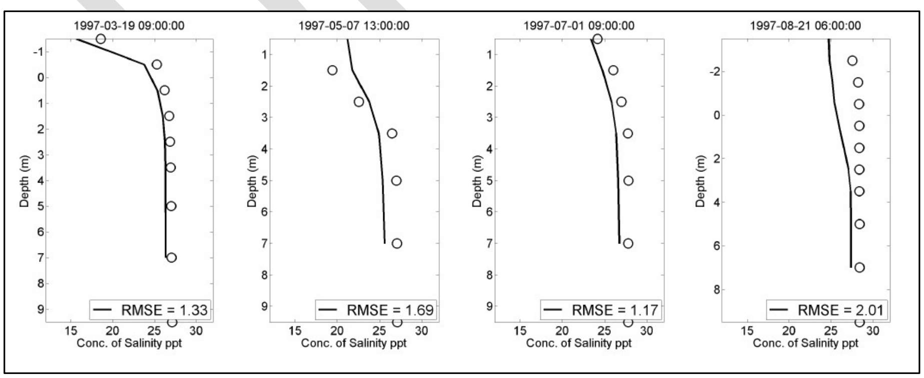
Diagnostic stations used for evaluation of temperature and salinity profiles and time series.



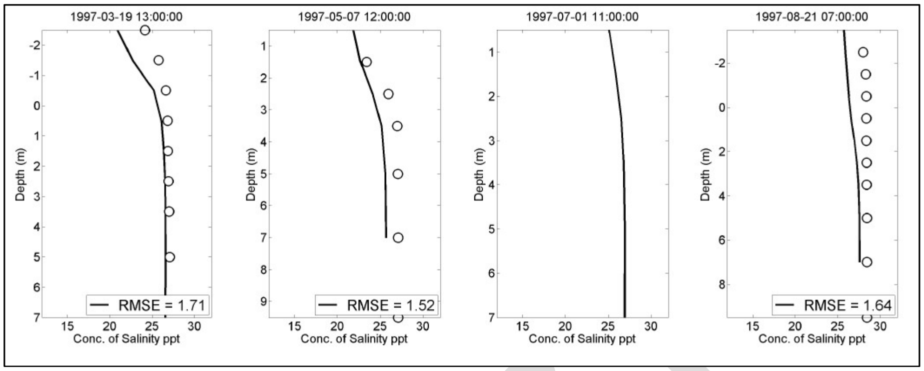
Salinity-Depth Profiles for Station B1-6



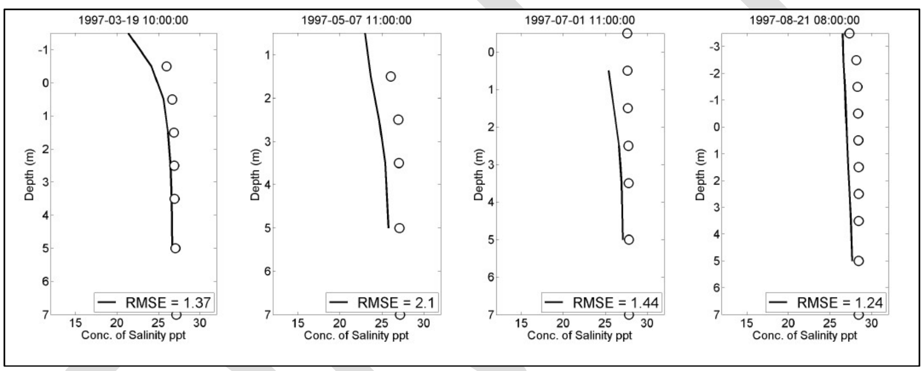
Salinity-Depth Profiles for Station B1-5



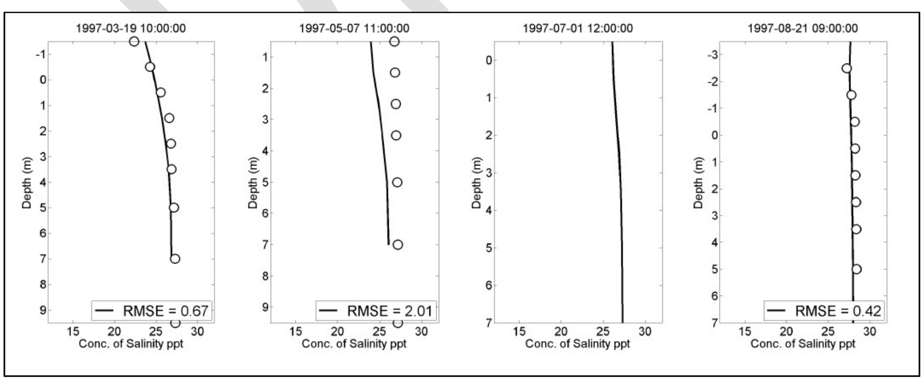
Salinity-Depth Profiles for Station B1-4



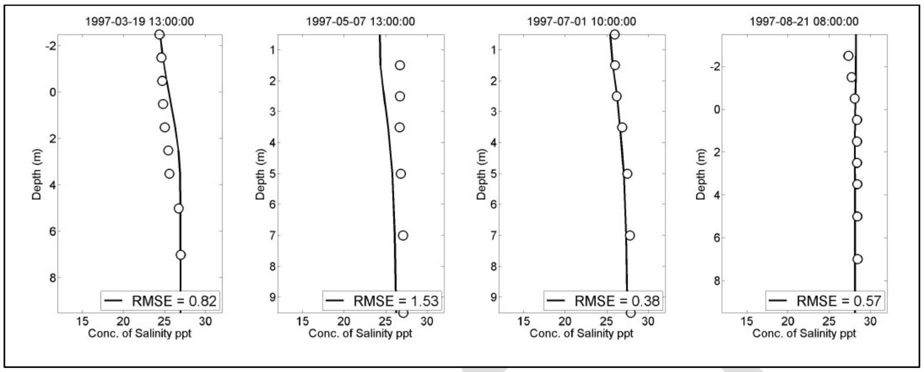
Salinity- Depth Profile for Station BA-2



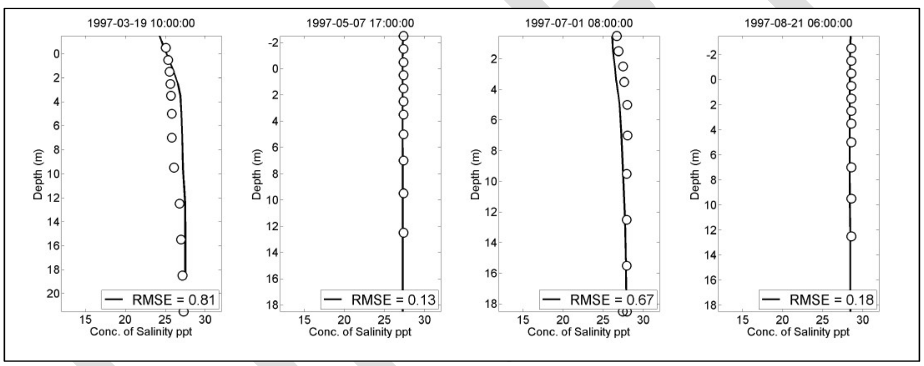
Salinity-Depth Profile for Station BB-2



Salinity-Depth Profile for Station BC-2



Salinity-Depth Profile for Station BD-2



Salinity-Depth Profile for Station BF-3